THE DOMINANT ROLE OF THE USER IN SEMICONDUCTOR AND ELECTRONIC SUBASSEMBLY PROCESS INNOVATION

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Abstract

In an earlier study of scientific instrument innovations, we found that instrument users rather than instrument manufacturers dominated the innovation work in approximately 80% of the innovation cases studied. In the present paper, we extend this work by examining 55 process innovations used in the manufacture of semiconductors and electronic subassemblies. In 67% of the process innovations studied in this field which involved novel process machinery, we find that it is the process machinery user rather than the manufacturer who "dominates" the innovation process by: recognizing the need; inventing a solution; building a prototype; and using the prototype in commercial production prior to any involvement of a manufacturer of process machinery in the innovation work.

The presence of a mix of user-dominated and manufacturer dominated innovation cases in our sample ("manufacturer dominated innovation" embraces those innovation cases in which the maximum user contribution was recognition of need) allowed us to test various parameters which we hoped would discriminate between these two innovation patterns. Our success at this effort was unfortunately low - the only strong pattern found was that users <u>always</u> dominated the innovation process leading to first commercial practice of a given manufacturing process step, while both patterns are found in the case of improvement innovations.

In a final section, the data and findings of three studies of process innovation in industries other than those studied by us are examined for indications of the innovative role played by the process user. The role of the user in each appears large, thus implying that the findings of our study may apply to process innovation in many industries.

The Dominant Role of the User in Semiconductor and Electronic Subassembly Process Innovation

1.0 INTRODUCTION

Over the past two years, we have been exploring the manner in which users and manufacturers of innovative industrial goods share the innovative processes which culminate in those goods. In our initial work, we focused on innovations in the scientific instrument industry.[1] In that industry, we found that approximately 80% of the innovations judged by users to offer them a significant increment in functional utility were in fact invented, prototyped, and first field tested by users of that instrument rather than by an instrument manufacturer. The role of the first commercial manufacturer of the innovative instrument in those cases was restricted, we found, to the performance of product engineering work on the user prototype (work which improved the prototype's reliability, "manufacturability" and convenience of operation, while leaving its principles of operation intact) and to the manufacture and sale of the resulting innovative product. Thus, our initial work presented us with the interesting picture of an industry widely regarded as innovative in which the firms comprising the industry are not necessarily innovative in themselves, but rather - in eight out of ten innovation cases - only provide the product engineering and manufacturing function for innovative instrument users.

Our findings regarding a "user dominated" innovation process in the scientific instrument industry is contrary to the prescriptive literature regarding the industrial good innovation process. Typically,

that literature[2,3] assumes that the manufacturer who aspires to commercialize an innovative industrial good must perform all the innovation work culminating in that good - and then proceeds to advise the manufacturing firm how best to manage each stage in that process, from gleam in the eye to that happy day when the completed device is placed on the market. Clearly, a different set of management prescriptions would be appropriate for a firm participating in an industry characterized by user dominated innovation.

In this paper, we will extend our study of patterns of innovation process sharing to a new "industry" - process machinery - rather than address managerial implications of user dominated innovation processes. It is appropriate to take this next step because:

- it is not clear a priori that a pattern found in scientific instruments will be found elsewhere. (When I present my results regarding the scientific instrument industry, I am occasionally told cheerfully that nothing found characteristic of scientific instrument innovation processes has anything to do with any other industry, as the scientific instrument industry is uniquely afflicted with users who are engineers and scientists in universities and industry);
- process machinery innovation is key to pressing national concerns of the moment such as increasing industrial productivity and improving the national balance of payments. Thus, if our study of process machinery innovation also shows a high level of user dominated innovation then we have generated a strong case for the importance of learning to manage innovation processes of this type.

Data to be presented in Section 4 of this paper will show that, as was found to be the case in the scientific instrument industry, users

of process machinery often do play a major role in the innovation process culminating in process machinery innovations. Since research results are strongly a function of definitions, sample selection criteria, and data collection methodology, however, we would like to define our terms "user dominated" and "manufacturer dominated" innovation processes (Section 2), describe our sample selection criteria (Section 3), and present details of our data collection methodology (Section 4) before proceeding to a discussion of our findings (Section 5). In Section 6, evidence bearing on the generality of our findings is discussed.

2.0 USER DOMINATED AND MANUFACTURER DOMINATED PATTERNS OF INNOVATION PROCESS SHARING DEFINED

In the pattern of innovation process sharing which we term "user dominated", it is an initial user of an industrial good innovation who:

- perceives the need for the innovative industrial good;
- conceives of a solution;
- builds a prototype device;
- proves the value of the prototype by using it;
- diffuses (intentionally or unintentionally) detailed information on the value of his "homemade" device and on how it may be replicated to other potential users and to firms which might be interested in manufacturing the device on a commercial basis.

Only when all of the above has transpired does the first commercial manufacturer become active in the innovation process. Typically, the manufacturer's contribution is then to:

- Perform product engineering work on the user's device to improve its reliability, convenience of operation, etc. (While this work may be extensive, it typically affects only the engineering embodiment of the user's invention, not its operating principles);
- Manufacture, market and sell the innovative product.

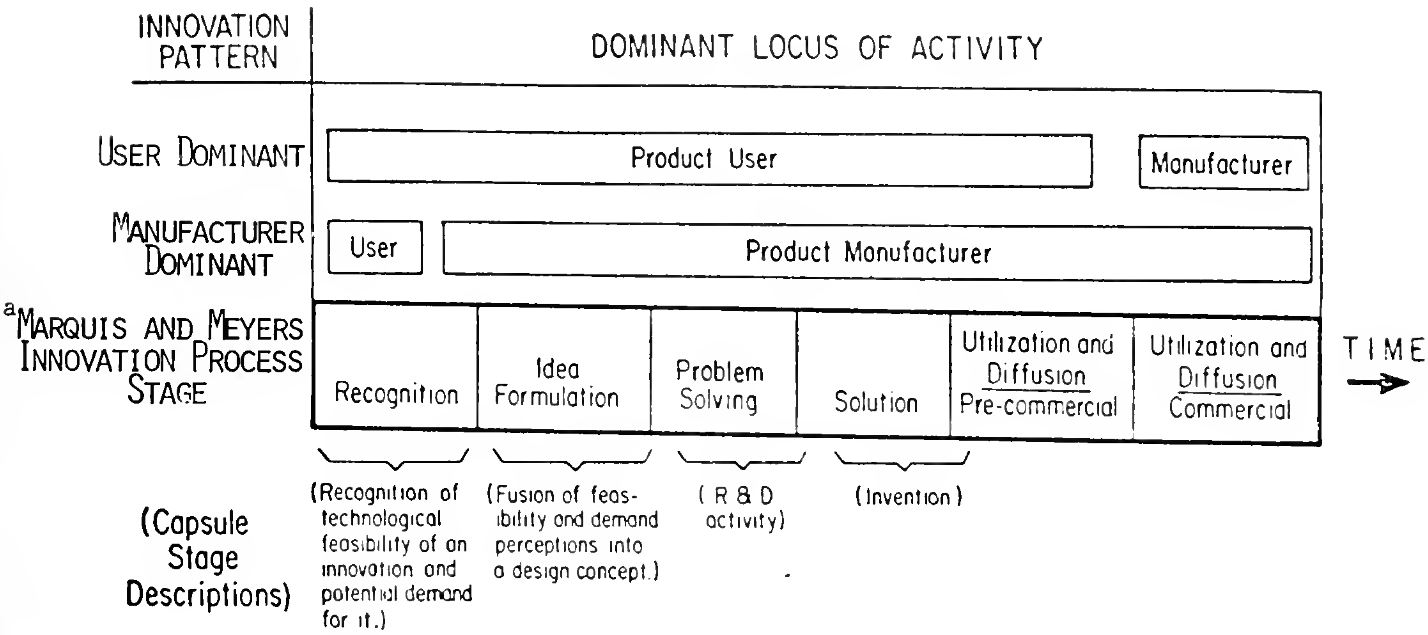
An example of a user dominated innovation process from our data on electronic subassembly manufacturing machinery innovations may help to give the reader the flavor of this pattern: IBM designed and built the first printed circuit card component insertion machine of the X-Y Table type to be used in commercial production. (IBM needed the machine to insert components into printed circuit cards which were in turn incorporated into computers.) After building and testing the design in-house, IBM, in 1959, sent engineering drawings of their design to a local machine builder along with an order for 8 units. The machine builder completed this and subsequent orders satisfactorily and later (1962) applied to IBM for permission to build essentially the same machine for sale on the open market. IBM agreed and the machine builder became the first commercial manufacturer of X-Y Table component insertion machines extant. (The above episode marked that firm's first entry into the component insertion equipment business. They are a major factor in the business today.)

The second pattern of innovation process sharing which we have observed and reported on - which we term "manufacturer dominated" - displays a more conventional distribution of innovation process activity between user and manufacturer. In this pattern, the maximum user role is a simple expression of need for an industrial good innovation to an interested manufacturer. The <u>manufacturer</u> then undertakes to conceive

of a responsive solution, and then to build, test, manufacture and sell the good with no further input from the user required.

If we were to chart these two patterns of user and manufacturer sharing of the innovation process against the stages of the innovation process as described by Marquis and Meyers,[4] they would look as follows:

Figure 1



[a]The names of stages and the capsule descriptions of them used in Figure 1 are taken from Marquis and Meyers,[4] p.4, Figure 1, "The Process of Technical Innovation," with but one alteration: We have divided Marquis' "Utilization and Diffusion" states into pre-commercial and commercial segments. We have done this because we have found that, in instances of user dominated innovation, substantial diffusion of an innovation among users often does take place prior to the first manufacture of the device for commercial sale and the "commercial utilization and diffusion" which then ensues. The innovation process stage of "precommercial utilization and diffusion" begins when "homebuilt" replicas of the original user innovation are first constructed and utilized by other members of the user community and ends when a commercial version of the innovation is first manufactured, sold and shipped ("date of first commercial shipment" is used to precisely locate end of stage).

2.1 Other Patterns of Innovation Process Sharing

The literature on innovation is replete with innovation case histories in which parties other than users of manufacturers of innovations are found to play a major role. The role of the independent inventor, for example, is highlighted by Jewkes, Sawers and Stillerman,[5] while Corey[6] examines cases in which "suppliers of new materials" play a dominant role in the innovation process. In our work, interestingly, we found no case in which parties other than users or manufacturers of a process machinery innovation played a significant role. We did find some cases, however, in which the user and manufacturer adopted a different mode of innovation process sharing than that defined as user dominated or manufacturer dominated. For example, in a few instances, we found that a user and a manufacturer would enter into a joint development effort and in effect share in all stages of the innovation process as these are defined by Marquis and Meyers. In our initial presentation of results, all these different modes of innovation process sharing between user and manufacturer will be lumped into a category entitled "other patterns of user-manufacturer sharing". Then at a later point in Section 5, the contents of this "other" category will be enumerated and described.

3.0 SAMPLE SELECTION CRITERIA AND THE SAMPLE

In this section we will identify the industries whose process innovations were selected for study, describe our criteria and procedures for sample selection within these industries, and explicitly identify the process innovations selected for the present study.

3.1 Industries Whose Process Innovations were Selected for Study

We chose to select our sample of process innovations from the universe of industrial processes used to:

- manufacture silicon-based semiconductors (such as transistors, integrated circuits, etc.);
- manufacture electronic subassemblies which are built up from electronic components mounted on printed circuit cards or boards with "wire wrapped" connections.

We focused on process innovations serving semiconductor and electronic subassembly firms not because we thought that the pattern we observed there would be representative of process innovation as a whole - in the present state of knowledge we have no way of knowing whether this is (or isn't) the case - but rather for the following two reasons:

- At the moment we are addressing our detailed studies of the innovation process to industry segments which <u>interact</u> to some degree, so that we may hope to observe interdependencies between industry segments as regards innovation processes - if such interdependencies do indeed exist - as well as within industry segment phenomena. (Our present roster of industry segments under study includes the instrument and computer industries - both of which use semiconductors and electronic subassemblies.) The reader

will not reap the fruits of this overall research plan until it has been moved farther along - but the choice of industries to be examined in this study was dictated in part by that plan;

- An early hypothesis raised by interviewees in semiconductor manufacturing firms as to why they, rather than the machinery manufacturers, appeared responsible for the bulk of the process innovations important to their industry, was that semiconductor manufacture offered challenges such as control of microscopic levels of chemical contamination, working on very small, precise parts, etc. that traditional machine builders found novel and were reluctant to address. The second industry chosen for study - electronic subassembly manufacture - offers a much more conventional type of challenge to machine builders and thus offers us a chance to test this hypothesis.

3.2 Criteria for Sample Selection

3.21 Rationale

If one looks at the "flow sheets" used to organize the process of manufacturing semiconductors and electronic subassemblies, one observes the presence of process "steps". The input and output of these process steps tend to remain constant over time although the technical means by which input is converted to output may change

drastically from time to time.[1] Manufacturing firms which build process machinery tend to focus on the equipment used in one or a few of these process steps, with the equipment addressed to each step forming a product line for the firm.

Our sample selection criteria are designed to allow us to explore the innovations impacting a subset of process steps exhaustively - at the cost of entirely excluding from our sample innovations related to some other process steps. Thus our sample includes 12 process innovations involving the soldering of electronic components to printed circuit boards but excludes all innovations involving the process step of testing the electronic functioning of the completed subassemblies.

We have chosen this sample design because its intensive focus on innovations related to a few process steps (thirteen, to be precise)

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[1] The following examples may serve to convey the flavor: In the process of making semiconductors, many circuits are fabricated simultaneously on a single wafer of silicon crystal. When completed, these circuits must be physically separated from each other and this is done by breaking the silicon wafer upon which they were fabricated into tiny square "chips" - each containing only one circuit. In the earliest days of the industry, this "scribing and dicing" function was carried out - as a consequence of a user dominated innovation process - by a worker who, with the aid of "jigs and fixtures", scratched lines manually between the circuits on a wafer with a sharp diamond point and then broke the wafer along those lines with the aid of a straight-edge. This manual process was slow and subject to worker error (for example, a worker might easily tire and scribe a line through the middle of some circuits instead of along their edges and thus ruin them), but when properly done, the input (wafers) and the output (chips) of the manual process was <u>precisely</u> the same as the input and output provided by succeeding generations of scribing and dicing machines. There have been several such generations of scribing and dicing equipment since the days when the job was done manually - some achieved by user dominated innovation processes and some by manufacturer dominated processes - and each has offered significant advantages over its predecessors such as higher speed, greater economy, etc. Sometimes the technical <u>means</u> by which the scribing and/or dicing is done has been changed - some recent machines use a laser beam to scribe the wafer instead of diamond points, for example - but, to reiterate, the inputs and outputs of all are identical.

maximizes our chances of perceiving innovation patterns of utility to real world firms whose product lines are similarly focused. For example, if the pattern of innovation process sharing changes as a line of process machinery "matures", or if the pattern differs for "major" versus "minor" innovations within a given product line, the sample design we have chosen should indicate this more clearly than a sample of equal size consisting of innovations selected randomly from the universe of all such impacting the manufacture of semiconductors and electronic subassemblies. This is so because meaningful comparisons regarding major versus minor innovations, etc., can be much more easily attained within the context of a given process step than across process steps - and our sample design maximized the need for the former type of comparison and minimizes the need for the latter.

3.22 Sample Selection

Our sample selection proceeded as follows:

(1) We identified all major process steps used at present to manufacture silicon based semiconductors and to manufacture electronic subassemblies mounted on printed circuit cards;[2]

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[2] The major process steps were identified by an examination of process flow sheets, discussion and plant visits with three Boston area manufacturers of semiconductors and two manufacturers of electronic subassemblies. We stopped after only these few consultations because: The experts were in substantial agreement as to the identity of process steps; the data we were beginning to generate on patterns of innovations did not appear to differ sharply for the different steps studied, implying that our findings would not be very sensitive to addition or deletion of any particular step.

Note that our focus on major process steps leads us to exclude:

- testing steps such as wafer probing and related innovations;
- transfer operations in which material-in-process is moved from station to station;
- minor process steps such as cleaning, the grinding of orientation flats on rods of single crystal, etc.

(2) We traced a subset[3] of the major process steps back to the method by which each was originally practiced commercially[4] and then, in conjunction with user experts, developed a list of major improvement innovations for each step which, when judged against best prevailing practice at the time of the innovation's first use in commercial manufacture, offered a significant increment in functional utility to the user firm;[5]

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[3]Since we began our data collection work planning to study all major process improvements for all major process steps used in semiconductor and electronic subassembly manufacture, the order in which we chose to study the process steps was haphazard rather than planned. When it became apparent that we only had time to study a subset of all process steps, we regretted our error: we are now not in a position to say that our choice of process steps to study in detail was random - only that it was done by no conscious system. In our sample of semiconductor process steps, the impact of our error should be minimal - we studied 11 of 16 steps identified. In our sample of electronic subassembly steps, where 2 of 4 steps identified were studied, the impact is less certain.

[4]Initial commercial practice of a process step occurs, in our definition, the first time the process step is used to manufacture semiconductors or electronic subassemblies intended for commercial sale rather than for internal experimental use of the manufacturing firm.

[5]Note that the importance of an innovation was judged relative to that of other innovations impacting the same process step - no attempt was made to compare the importance of innovations impacting different process steps.

Our initial attempts to get consensus on a list of important process innovations from the users of such innovations - that is, manufacturing engineers in semiconductor and electronic subassembly manufacturing companies - were not encouraging. The breadth and depth of understanding evidenced by various interviewees seemed to us so disparate that a mere summing of opinions would be meaningless. The method we finally used was to:

- Decide independently for each process step studied which of our interviewees seemed to have the best grasp of innovation in that process step and its utility to the user and base our list on his (their) opinion. (Both of the research assistants involved in this project as well as myself have engineering training and several years of industrial experience. The reader might find this reassuring evidence that, if ignorance is bliss, we did not assess the relative merits of our interviewees' opinions with an entirely blissful mindset);

- Explicitly list the sample of innovations finally selected so that other experts in the field will have an opportunity to judge its appropriateness for themselves (cf. Table 1).

The initial commercial practice and all significant improvement innovations identified and in commercial use prior to 1971[6] were then included in our sample;

(3) For one randomly selected process step in semiconductor manufacture (coating of the silicon substrate wafer with photographic resist) and for one randomly selected process step in electronic subassembly manufacture (soldering of the components to the printed circuit board) we tried to identify all minor process improvements and included these in a separate sample with the aim of determining whether the innovation pattern observed for innovations of major functional importance also hold for minor innovations.[7]

Note that the sample generated by application of the above criteria is a sample of process innovations which may or may not be embodied in novel process machinery. All innovations in the sample were successful in the sense of receiving widespread use in their respective industries. In those cases where novel process equipment was involved, that equipment became a commercially viable industrial good, manufactured for commercial sale by at least one (and usually several) process equipment firms.

Second and subsequent "me-too" commercializations of a functionally significant innovation by manufacturing firms are excluded from the

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[6] We excluded process innovations less than 5 years old from our sample simply because we felt that they were too new for their significance to be fairly judged.

[7] The minor innovations selected for study were generated by canvassing all U.S. firms manufacturing wafer resist coating and board soldering equipment as well as many users of such equipment and asking them to list all improvements they could recall which offered any incremental utility to a user under any special circumstances of use. (Thus, one of the innovations included in the list of minor board soldering innovations was an inclined rather than a flat conveyor to carry boards away from the wave soldering machine - a change which helped prevent "icicles" of solder from forming under the soldered boards under certain conditions of operation of that machine.)

sample, as are second and subsequent innovations in which the <u>same</u> functional result is attained by a technical means <u>different</u> from that employed by the initially commercialized version.[8] Also excluded is that type of innovation which Clark[7] and Knight[8] have termed unidentified engineering and production improvements.[9]

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[8]Our reason for employing this pair of selection rules is as follows: Based on anecdotal evidence, we expect that the innovation process leading to <u>functionally</u> novel industrial good innovations differs from that which produces "me-too" and "functional me-too" innovations incorporating technically novel means. Since our data-gathering resources are finite, we have felt it prudent to eliminate this source of variance from our sample by focusing our investigations on only one of these innovation types. Of the three innovation types, we have chosen to focus on those which first commercialize some functional novelty of significant utility to users because we feel that this type of innovation provides the greatest utility to society as a whole. Further - and again based on anecdotal evidence - we feel that the innovation process which leads to functionally novel innovations is currently the least understood and/or empirically least well-managed of the three types. Note that individual firms may undertake "me-too" innovations far more frequently than functionally novel ones. (As a hypothetical illustration, consider an industry consisting of 10 firms, each committed to offering the consumer a product line containing all functional capabilities offered by any of its nine competitors. By definition, then, each innovation offered by one of the ten firms which provides the customer a novel and useful function will trigger nine "me-too" (or possibly "me better") innovations - and, in aggregate, 90% of the industry's new product introductions will be "me-too's".)

[9]As we have noted, our sample selection methodology solicits from interviewees process innovations which they perceive to have offered incremental functional utility to users. An examination of the sample thus generated will show that each innovation identified has a unique feature or features which distinguishes it from previous practice and it is the genesis of these features which are traced in our innovation case histories. Clark and Knight have developed a different methodology for selecting a sample of innovations and have applied it to the case of jet engines and computers respectively. Their methodology involves tracing the improvement of certain performance dimensions over time (an example of a dimension used in the study of computers is cycles per second) whose improvement presumably offers incremental utility to the user. Computer or jet engine models which show a significant improvement on such dimensions relative to best previous practice are identified and become the sample of innovations to be subjected to study. Interestingly, Clark and Knight have found that in approximately half the cases selected for study, the significant performance improvements displayed by the computers or jet engines could <u>not</u> be traced to a particular feature or features of the improved device. In such instances, the performance improvements were apparently attributable to many samll component and system configuration improvements whose individual impacts are small and which they could not

The identity of the major process steps and improvements which emerged from our sample selection process and whose innovation histories we studied are as follows:

Table 1. Identity of Sample

FOR MANUFACTURE OF SILICON SEMICONDUCTOR PRODUCTS[e]

Major Process Step	Initial Commercial Practice	Major Improvement
1. Growth of Single Silicon Crystal[c]	RF Crystal Puller	Resist Heated Crystal Pulling Dislocation Free Crystal Pulling[a] Auto Diameter Control
2. Wafer Slicing	High Precision Saws[b]	ID Saw
3. Wafer Lapping and Polishing	Optical Polishing[b] equipment and technique	Chem-mech Polishing (SiO_2)[a] Chem-mech Polishing (Copper)[a]
4. Epitaxial Processing (optional)	Pancake Reactor	Horizontal Reactor Barrel Reactor
5. Oxidation	NOT EXAMINED	
6. Resist Coating	Wafer Spinner	High Accel. Wafer Spinner 11 minor improvement innovations
7. Mask Alignment and Wafer Exposure	Mask Aligner	Split Field Optics Aligner Auto Mask Aligner
8. Oxide Etching	NOT EXAMINED	
9. Junction Fabrication in Silicon[e]	Grown Junction[a]	Diffused Junction (Furnace) Ion Implantation Accelerator
10. Metalization	NOT EXAMINED	
11. Scribing and Dicing	Jig & Fixture[a]	Mechanical Scriber and Dicer Laser Scriber and Dicer
12. Mounting	NOT EXAMINED	
13. Wire Bonding	Solder Bonding[d]	Thermocompression Bonding Ultrasonic Bonding
14. Encapsulation	NOT EXAMINED	

(continued on next page)

(continued)
isolate, but which in net add up to a significant performance improvement. Clark and Knight's term for this source of improvement is, graphically enough, "Undisclosed engineering and production improvements". It should be noted that this type of innovation is not represented in our sample.

Table 1 (continued)

Major Process Step	Initial Commercial Practice	Major Improvement
Major Mask Preparation Steps[g]		
15. Mask Graphics	Handcut Rubylith[a] Patterns	NC (Optical) Pattern Generator NC (Electron Beam) Pattern Generator
16. Mask Reduction	Two stage step and repeat reduction process	
FOR ELECTRONIC SUBASSEMBLY MANUFACTURE		
1. Circuit Fabrication	Printed Circuit Card[b]	NOT EXAMINED
	Wire Wrapping (optional)[f]	NC Wire Wrapping (optional)[f]
2. Component Insertion	Hand Component Insertion[a]	Single-component-per-station Component Insertion X-Y Table Component Insertion NC Driven X-Y Table Component Insertion Sequenced Component Insertion
3. Mass Soldering	Dip Solder	Wave Solder 9 minor improvement innovations
4. Assembly Testing	NOT EXAMINED	

[a] This process innovation was embodied primarily in operator technique rather than in novel process equipment. This type of process innovation is not lumped with those involving novel process equipment in our data analysis.

[b] The process machinery utilized in the initial commercial practice of this process step was commercially available and being used in other industries. Innovation work needed in these instances consisted simply of identifying the equipment as appropriate for the process step contemplated and/or redefining the process step specifications until they fit the capabilities of that equipment. Adopted equipment is not lumped with novel process equipment in our data analyses.

[c] Float zone refining and dislocation-free float zone refining offer an alternate silicon single crystal growing technology. We have not included these in our sample because a great deal of the innovation work involved in adapting the process to the manufacture of single silicon crystals was done abroad (largely by Siemans, a user of the process) and data regarding it was thus relatively inaccessible to us. Until very recently, the float zone process was little used in this country for commercial production of such crystals.

[d] Although developed by user firms and widely implemented by them by means of homebuilt equipment, this innovation was superceded by thermocompression bonding before a commercial version of the equipment was placed on the marketplace. As a consequence it was <u>not</u> included in our data analysis.

Table 1 (continued)

[e]Point contact junctions, alloy junctions and electrochemical junction machining (also known as "jet etching") appear in Golding's[9] and/or Tilton's[10] list of important process innovations in semiconductor processing. We exclude them because they were used entirely or almost entirely in the fabrication of Germanium rather than silicon semiconductors.

[f]Wire wrap terminals are sometimes inserted into printed circuit cards to allow that additional mode of interconnection.

[g]These two "process steps" are key to semiconductor manufacture but, unlike the other steps sampled, are not addressed directly to the devices being manufactured but rather to the "tooling" (masks) used in Step 7.

A final note before we leave the topic of sample selection. To date, we have consciously elected to limit our investigations to those industries in which the firms which manufacture innovative industrial goods do not, typically, also contain groups who have a need to use those goods. We have done this simply to allow us to more reliably distinguish innovation users from innovation manufacturers. If the manufacturers and users of an innovation are not found in the same firm. we can use organizational boundaries as an aid in determining in retrospect whether a particular innovation was developed because a firm wished to use it or because it wished to make a business of manufacturing and selling the innovation for others to use. In the industries we have studied to date, this distinction is clearcut: Firms which manufacture semiconductor process machinery, for example, typically do not make semiconductors - and therefore, typically, do not innovate in this field because they themselves have a use for the innovative machinery. In many industries which we have not yet studied the distinction between users and manufacturers of innovations cannot be made with the aid of organizational boundaries. For example, some of the most sophisticated users of computers and such electrical measuring instruments as oscilloscopes are at work in the firms which manufacture these items. In such

industries one cannot distinguish between user dominated and manufacturer dominated innovations by stationing an observer, in effect, at the boundary of the firm.[10]

4.0 DATA COLLECTION METHODOLOGY

Once we had identified a sample of innovations for study, we sought out essentially <u>every</u> potential source of information on issues of interest to us. Data collection involved the following steps:

(1) Typically, we would start our work by identifying the first firm to commercialize an innovation and the date of commercial introduction (defined as date of first commercial unit shipped). This would be done by asking personnel of firms now manufacturing "me-too" devices if they knew who the first firm to commercialize was, <u>and</u> asking expert users of the innovation. Ambiguities were cleared up by a search of back issues of trade journals, seeking the earliest advertisements and/or new product announcements for the innovation in question.

(2) When the first commercializing firm and the date of commercialization was firmly established:

- We interviewed, usually by telephone, everyone at the commercializing firm who claimed to have been directly involved in the innovation work or to have knowledge of it. Each of these interviewees was asked, as a routine part of

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[10] By stating that we can today use organizational boundaries to distinguish reasonably clearly between users and manufacturers of scientific instruments and process machinery, we do not mean to imply that this condition will always hold in these industries. In the last few years DuPont, for example, has become a manufacturer as well as a user of scientific instruments - partially in order to profit from manufacturing and diffusing innovations developed by instrument users in DuPont's chemical research laboratories. If this becomes a trend, the current organizational distinction between users and manufacturers of scientific instruments would erode in future.

the structured interview, to provide the names of others he felt might have some information to contribute and these individuals were telephoned in turn. We were persistent in our efforts to contact all individuals named and were not daunted when we had to trace them through several changes of employment or to retirement addresses;[11]

- In parallel to our interviews with personnel of first-commercializing firms we searched the appropriate technical literature in the period prior to first commercial innovation, seeking references to experimental apparatus functionally similar to the commercialized innovation or other relevant work. Authors of relevant journal articles were contacted and interviewed regarding their knowledge of work going on in the user community or general scientific community relevant to the innovation being studied and occuring prior to its commercialization. Any information they had as to the possible transfer of such information to user firms and/or to the first commercializing firm was solicited as well as names of any others who might know of such transfer - or the lack of it;

- Also in parallel to our interviews with personnel of first-commercializing firms, we sought out and interviewed personnel in user-innovator firms if we had identified such. If we had no information from the first commercial manufacturer or the technical literature and related interviewees regarding the presence of user-innovators, we attempted to assure ourselves insofar as we could that such indeed did not exist by canvassing logical potential user innovator firms (e.g., Fairchild Semiconductor and Texas Instruments for early semiconductor manufacturing equipment innovations) for

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[11]We would like to reassure those who hold the right of privacy dear - as do we. Chilling images of researchers waving tape recorders and notebooks as they mount assaults on frailly-guarded rest-home gates are inappropriate here. In reality almost everyone we contacted was delighted to talk to someone with a scholarly interest in the successful (recall our sample selection criteria) innovation in which he or she had played a role or known about. And obviously, the wishes of the very few who did not wish to talk with us were instantly complied with.

information. Where we could identify very early purchasers of the commercialized innovation, we also canvassed these firms for information regarding any contribution of theirs to the innovation and/or name of individuals who might have information bearing on the innovation process, etc.

(3) Information from these various sources was assembled, discrepancies noted, and interviewees with information bearing on the discrepancies contacted again for further discussion. Some areas of confusion were cleared up by this process, others were not. We always attempted to accurately preserve differing versions of events where they existed, and did not attempt to determine "who was right". If proper coding of an item would require us to make such a judgment, we coded it NA (Not Available). As a final step, key interviewees were sent written protocols of what they said as we understood it - for a final check of accuracy and/or correction of our information.

The reader may wonder at such a laborious and multi-sources data-gathering effort. Unfortunately, we have found it necessary.[12]

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[12] In the course of our work we have rediscovered, with combined amusement and dismay, the ancient principle that "success has many fathers". Also, we have found that one "father", interviewed on the history of an innovation, will very possibly not even mention the existence of other "pretenders" to that title, thus necessitating that we identify such by canvassing independent sources as was described above.

A short anecdote may serve to give the reader the flavor of the problem. We enquired of the responsible project engineer at what was apparently the first commercial manufacturer of an instrument as to its innovation history. "All mine," he said, "from gleam in the eye to the polished device you see before you." "No inputs as to need or solution and/or any known functional antecedants from any source, inside or outside, living or dead?" we asked. "None." We went home, much impressed, and ran a computer search of Chemical Abstracts. Up popped three articles published several years before describing experimental versions of the innovation and the interesting results obtained through their use. A search of trade journal ads which we conducted in parallel produced information about a functionally equivalent Canadian instrument which had apparently been introduced to the marketplace prior to the introduction of the American company's version. We went

It has been our experience that independent identification by the researcher of users, manufacturers, and others who may have played a role in an innovation will typically yield a much more balanced account of the innovation history than will an approach which identifies one innovation participant and then relies totally on that person to identify other innovation participants. If, for example, we had relied exclusively on manufacturers to identify user innovators who had contributed to the innovations which we studied, many of these would not have become known to us.

(continued)
back to our original informant to discuss these findings. He said in honest confusion that, while he was aware of the articles and product which we had found, he had not mentioned them to us because he did not consider them to be related to his innovation. While, to be sure, the function and operating principles of the experimental devices and the Canadian product were the same as his, the product engineering of his was entirely his own - and this had been the innovation in his view.

After further amiable discussion, we were able to understand each others terminology and intent better and the product engineer volunteered that the author of one of the articles had been a consultant on his project. This happily cleared up a final concern of ours, because we had previously been told of the consulting arrangement by the author of the article in question when we had contacted him. (From that expert's point of view, parenthetically, the contribution of the commercializing firm to the innovation had been "only a pretty packaging job.")

Thus endeth our cautionary tale - we mercifully spare our readers from the details of how we trudged on to search out the first commercial version of that particular innovation.

5.0 FINDINGS AND DISCUSSION

Process innovation involves more than the development of innovative types of process machinery. For example, an important process innovation might be embodied in novel operator technique rather than in equipment. Recognizing this, we designed our sample selection criteria to screen for innovations functionally important to the user independent of whether these involved any novel hardware. The result of this decision is that a few important process innovations not involving novel process hardware did turn up in our sample. Since our sample size of innovations not involving novel hardware is small, and since it raises issues not germane to innovations which do involve novel hardware, we will break our presentation of findings into two segments. In Sections 5.1 and 5.2, we will consider only process innovations in our sample involving novel process hardware, and in Section 5.3 we will consider process innovations not meeting this condition.

5.1 The User's Role in Process Innovations Involving Novel Process Machinery

As can be seen clearly from the data in Table 2, we have found user dominated innovation patterns to be very strongly present in the segments of the process machinery industry sampled. All of the novel process machinery used in the initial commercial practice of a process step and more than 60% of the improvements to that machinery were, we found, invented, prototyped and used in commercial production by innovative users prior to being manufactured for sale by process machinery manufacturing companies.

Table 2. Innovation Pattern Observed for Process Machinery Innovations

		1	2	3	4	5	6	7
		Innovation Process Dominated by			# Other User-Mfr Pattern	# Non-User-Mfr Pattern	# NA	# Total
		% User	# User	# Mfr				
Semiconductor Processing Innovation	Initial Comm'l Practice	100%	5	0	0	0	0	5
	Major Improvement	71%	10	2	2	0	2	16
	Minor Improvement	56%	5	3	1	0	2	11
Electronic Subassembly Processing Innovation	Initial Comm'l Practice	100%	2	0	0	0	0	2
	Major Improvement	40%	2	2	1	0	1	6
	Minor Improvement	62%	5	2	1	0	1	9
	Total	67%	29	9	5	0	6	49

Note that we observed no cases of innovation (Table 2, Column 5) in which parties other than users and manufacturers of process machinery played a significant role.[13]

From Column 4, Table 2 we find that an exclusive focus on cases of user dominated innovation found in our sample somewhat understates the actual level of user participation in the innovation process. In five cases we have found that while the users did not carry the innovation work far enough to meet the criteria for user dominated innovation, they carried it farther than required by the criteria for manufacturer dominated

[13] See Section 2.1 for references to studies of innovation in which "third parties" such as independent inventors were found to play a major role.

innovation.[14] In four of these cases, the users provided machinery manufacturers with the central technical solution concept used in the innovation as well as the need. (Thus, in the case of ultrasonic wire bonding, users approached a company specializing in the manufacture of ultrasonic transducers with the suggestion that a metallurgically desirable aluminum to aluminum bond could be achieved with a bonding tool using ultrasonics.) In an additional two cases, user firms went even further and prototyped the desired device and made the information gained from this step available to the manufacturing firm which eventually built the first commercially used device. In only one such case was that information actually used by the manufacturing firm, however.

In Table 3 below, the amount of innovation work done by users prior to first commercialization of an innovation and the proportion of that work actually utilized by manufacturers of the first commercial device is laid out graphically. (We could reliably obtain this information for only 37 of the 49 cases of innovation in our sample which involved novel process machinery.)

Note that manufacturers usually did utilize and build upon user innovation efforts. The scenario suggested by the "not invented here" syndrome, e.g. manufacturers deciding that solutions developed by users must be done over from scratch, does not appear salient here. In that sense at least, user dominated and user shared innovation processes seem efficient.

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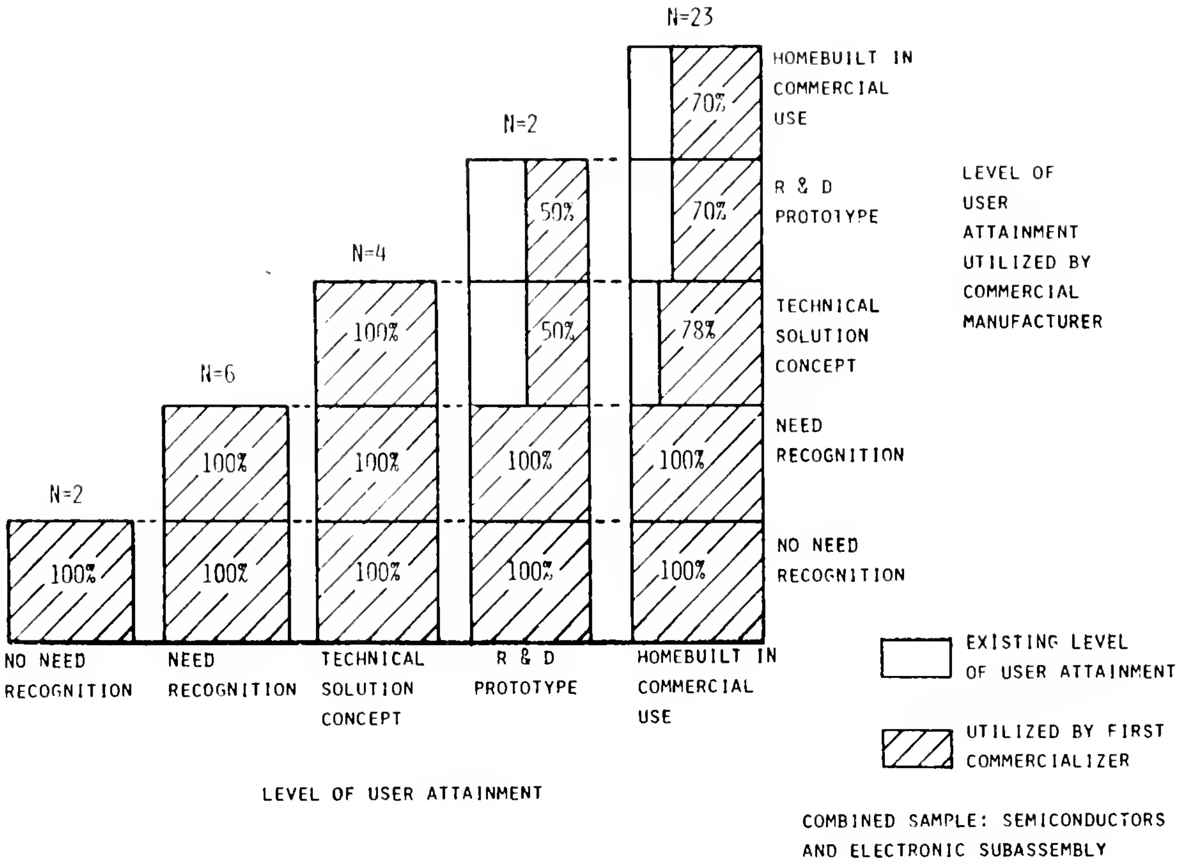
[14] Four percent of our sample of scientific instrument innovations also fell into such an "in-between" pattern of innovation process sharing. In our paper reporting on that work, we noted that we would code all such cases as manufacturer dominated in order to take a conservative stand toward our hypothesis regarding the existence and salience of user dominated innovation. (Cf. von Hippel, "The Dominant Role of Users in the Scientific Instrument Innovation Process", Research Policy, forthcoming, Section 3.1, Footnote 7.)

Table 3. Innovation Work Performed by User Prior to Commercialization



[a]Stage names used in Table 3 are hopefully self-explanatory: "Need Recognition" by the user means that the user(s) pointed out a problem to suppliers - e.g., "This way of soldering printed circuit boards is terrible!" - without suggesting a solution; "Technical Solution Concept" by users means that the user(s) pointed out how the need should be met - e.g., "This bond would be better made if ultrasonic bonding techniques were used."

5.2 A Search for Parameters Which Co-vary with the Level of User Participation in the Innovation Process

One of our hopes when we embarked on our study of the user's role in process machinery innovation was that we would find a sufficient number of <u>both</u> user and manufacturer dominated innovation cases so

that we would have an opportunity to seek parameters which discriminate between them. Alas, as was the case in scientific instrument innovations, users have swept the field to such a degree that we only have nine cases of manufacturer dominated innovation in our sample as compared with 29 cases of user dominated innovation. Never ones to reject a quixotic challenge, however, we did strive to discern parameters differentially correlated with the presence of user and manufacturer dominated innovation, with the results described below.

5.21 Innovation Process Sharing Patterns as a Function of Level of Utility of Innovation

As previously noted, Table 2 indicates that process machinery used in the initial commercial practice of a process step is always developed by a user dominated innovation pattern, while major and minor improvement innovations display a mixture of user dominated, manufacturer dominated and occasionally "other" patterns of user-manufacturer innovation process sharing (cf. Section 5.1 for a discussion of "other" patterns). Application of a chi square test to this pattern (e.g., to initial practice vs. major plus minor improvement innovations and to user dominated vs. manufacturer dominated plus "other" patterns) brings the happy news that the pattern is statistically significant ($p < .05$). Additionally, we feel that this pattern passes a test of reason in that the incentive for manufacturers of process machinery to innovate would appear to be greater in the instance of major and minor process step improvements than would be the case for initial process step practice. We feel that this is so because equipment improving process step practice is addressed to a market opportunity which is both more certain (because the utility of the process has been demonstrated) and larger (because the user industry has grown) than was available when innovative machinery

initial process step practice was needed.

5.22 Pattern of Innovation Process Sharing as a Function of Time

It has been suggested by Utterback and Abernathy[11] that the locus of innovation shifts as the industry matures from user to machinery producer. Olsen[12], on the other hand, has observed patent activity to shift from machinery producer to user over time in the instance of major textile machinery innovations. We ourselves found no significant trend in pattern of innovation vs. calendar time over the time spans examined.[15] As the results of Section 5.21 indicate, however, if our time scale is adjusted so that initial practice of each process step is regarded as time zero, and times of initial commercialization of additional innovations impacting that process step measured relative to that time zero, the results do show a significant increase in manufacturer dominated and "other" innovation patterns relative to user dominated patterns with the passage of time.

5.23 Innovation Process Sharing Patterns as a Function of Industry

Interestingly, the data displayed in Table 3 does not look very different for the two industries studied. As we mentioned in our discussion of sample selection criteria above, interviewees in the semiconductor manufacturing industry had suggested that we would find their role in process machinery development unusually large because of the novel challenges semiconductor machinery design presented to

[15] The first silicon semiconductor was commercialized in 1954, and thus our sample of semiconductor process innovations starts with that date and continues to 1971 (cf. footnote 11). The first electronic subassembly mounted on a printed circuit board was commercialized in 1949 and thus our sample of electronic subassembly process innovations start with that date and continues to 1971 (cf. footnote 11).

machine builders - novel challenges not present in the instance of electronic subassembly process equipment design.[16] A significant difference in the hypothesized direction was not found.

5.24 A Hypothesis not Tested

There was a hypothesis regarding the causes of user dominated vs. manufacturer dominated innovation which we wanted to test, tried to test, but, alas, failed to test. It was that manufacturer dominated innovation is characteristic of innovations of large market potential, while user dominated innovation process is characteristic of innovations of small market potential which manufacturers "don't want to bother with". When we attempted to test this hypothesis by gathering sales data on process machinery innovations, we found that the confidentiality of sales data was apparently prized more highly than life itself by manufacturers (we hasten to point out that we did not attempt to put that hypothesis to the test), and so our attempt failed.

5.3 Process Innovation Not Involving Novel Process Machinery

As was noted at the start of Section 5, process innovation involves more than the development of innovative process machinery. And, indeed,

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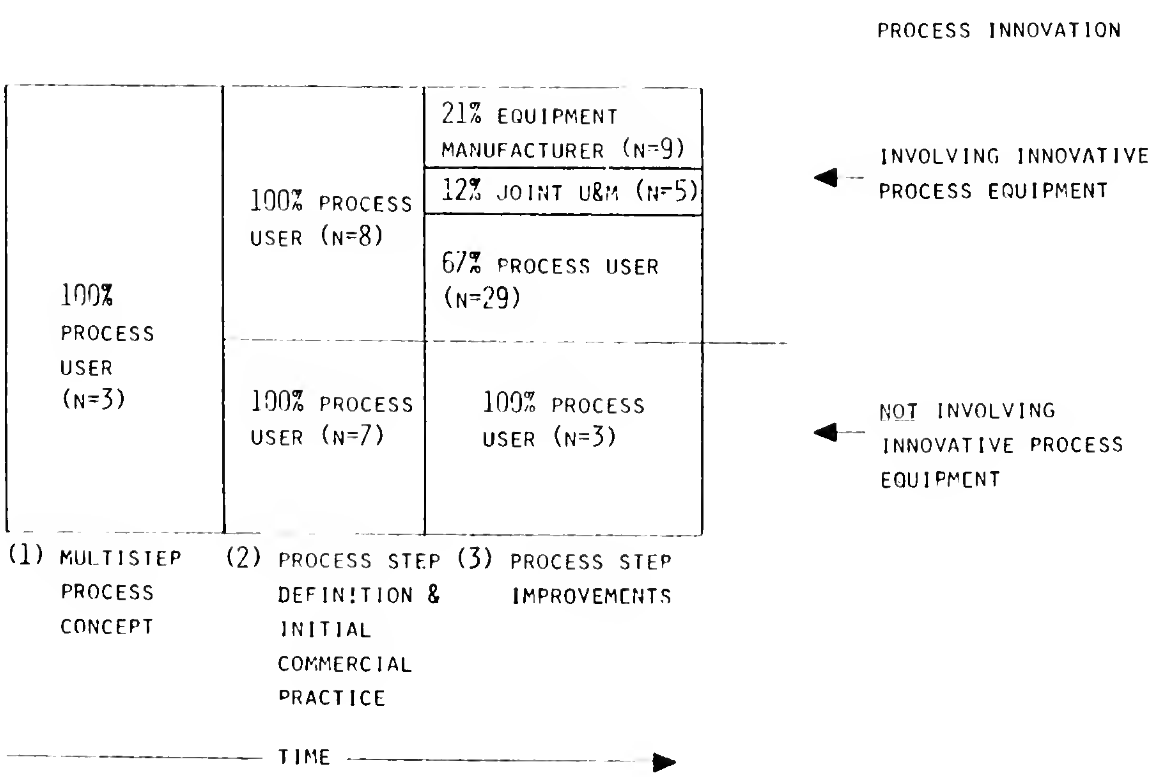
[16] Novel machine design challenges offered by semiconductor manufacturing processes lay primarily in the areas of control of chemical contamination (introduction of impurities at the level of parts-per-million can radically change the operating characteristics of semiconductor devices) and in the area of physical size. Operations such as bonding of wires to semiconductor circuits demanded production machinery which would reliably and precisely carry out physical operations on a scale so small they could only be seen under a microscope - a difficult problem with no precedent in any preceeding type of manufacture. In contrast, the processes involved in electronic subassembly manufacture - the automatic insertion of components into mounting holes with a level of precision quite usual for many mechanical assembly operations, for example - offered challenges well within the standard range for builders of machines used in mechanical assembly processes.

in the course of our work on process innovation, we have studied several cases of important innovation which do not involve such machinery. Although the sample sizes are small, we feel it important to present our findings regarding these cases, because it will serve to set our work regarding process machinery into the larger context of all process innovation.

For purposes of the present discussion, it will be useful to distinguish three "levels" of process innovation. The identity of these levels - as well as a summary indication of our sample sizes and our findings regarding the degree of involvement of process users and process equipment manufacturers in each - is shown schematically in Figure 2 below.

Figure 2. Roles of Process Users and Equipment Manufacturers in Process Innovation



The reader may note that process innovation moves from left to right on Figure 2 with the passage of time, and further note that to this point in our discussion of findings we have only considered process innovation of the types represented by the upper portion of columns 2 and 3 in that figure. In the sections which follow, we will briefly consider our findings regarding innovations of the types noted in Figure 2 and not yet touched upon, viz.: multistep process concepts; process step definition and initial commercial practice where innovative process equipment is not involved; and process step improvements where innovative process equipment is not involved.

5.31 Role of the User in Development of Multistep Process Concept

Larger process concepts underlie the individual process steps which we have identified in Table 1 and give these meaning. For example, process steps 5 through 10 in that table are steps in a photolithographic process which all have utility only in the context of a larger process concept known as the planar process of semiconductor manufacture.[17]

We did not explicitly seek out process concepts impacting multiple process steps, and the reader will note that none are represented in Table 1, Identity of Sample. We did, however, study three such concepts "along the way" and found that all were developed by process users with no participation by equipment manufacturers. One of these, as mentioned above, was the planar process concept of semiconductor manufacture

[17] Tilton[10] and Golding[9] note that many semiconductor process innovations are associated with product innovations - e.g., the planar process gave rise to the planar semiconductor. We focus in this paper on the process aspect of these innovations only.

developed by Fairchild - a semiconductor manufacturing company - which was first used to produce commercial devices in 1960. The second process concept impacting multiple process steps which we studied provided the starting point for our study of semiconductor innovation, and was the introduction of silicon as substrate material upon which to build semiconductors. Silicon transistors were first produced in commercial quantities by Texas Instruments in 1954. The third multistep process concept which we studied was the building of electronic subassemblies on printed circuit cards. This innovation represented the starting point for our study of electronic subassembly process innovations, and was developed by the U.S. Signal Corps in 1948 as part of an effort to miniaturize military electronics.

All of these process concepts were developed by users of the processes, we have found, with no participation by equipment manufacturers. This should not be regarded as an obvious finding - Corey[6] has documented cases in which suppliers of new materials develop new products made from those materials and the processes by which those products will be made - in the interests of increasing sales of the materials. Also, we ourselves have found instances, in the course of exploratory probes into a range of industries, of processes developed by equipment suppliers - in the interests of selling more equipment.

5.32 Role of the User in Process Step Innovation Not Involving Process Machinery

The remaining two categories of Figure 1 to be considered - initial process step practice and improvements to this practice which do not involve innovative hardware - are represented in our study by the sample shown in Table 4, below.

Table 4. Process Innovations not Requiring Novel Process Equipment for Implementation

Industry	Process Innovation Implemented via:	Number of Cases in Sample: Initial Process Step Practice	Number of Cases in Sample: Process Step Improvements	Innovation Work By:
Semiconductor Manufacture	Manual Operator Technique[a]	3	3	100% user
	Application of Commercially Available Process Equipment[b]	2	0	100% user
Electronic Subassembly Manufacture	Manual Operator Technique[a]	1	0	100% user
	Application of Commercially Available Process Equipment[b]	1	0	100% user
Total		7	3	

[a]Process innovations of this type in our sample are identified in Table 1 by the superscript "a".

[b]Process innovations of this type in our sample are identified in Table 1 by the superscript "b". Innovation work by users in these instances consists of identifying the equipment as appropriate to the process step at hand (and/or redefining the process step task until it fits the capabilities of commercially available equipment) and applying it.

As an example of an important process innovation implemented without need for novel processing equipment, consider dislocation-free crystal growing. Pioneered by Dash at GE (a user firm), its implementation involved "fine-tuning" of existing crystal growing equipment rather than any novel hardware. As an example of implementation of a process step by adoption of commercially available equipment, consider the early use of commercial optical polishing equipment for the process

step of polishing silicon wafers. All innovations which we found which did not require innovative hardware were "user dominated". One would expect this to be the case where no hardware is involved in an innovation - manufacturers have no incentive to play a role in either developing or diffusing these. Manufacturers would have an interest in finding new applications for products currently being sold by them, however, so we cannot discount the possibility that they would play a role in developing and diffusing innovations requiring non-innovative hardware - of their manufacture. However, we did not observe any instances of this type of behavior by manufacturers in the present sample.

Note that the semiconductor and electronic subassembly manufacturing industries appear not to have benefited much via adoption of process machinery originally developed to serve other fields. A comparison of the data on Tables 2 and 4 shows that only 25% of initial commercial practice of process steps was implemented by adopting commercially available process machinery. No process improvement was achieved via use of machinery adopted from another field.

6.0 GENERALIZABILITY OF FINDINGS

We have explored the sources of process innovation serving two industries - semiconductor manufacture and electronic subassembly manufacture - in some detail, and have found that process users are responsible for much of it. Can this finding be generalized to innovative processes and associated equipment serving other industries as well? We have found three studies containing data bearing on this issue, and they tend to support such a possibility, as follows:

(1) Hollander[18], in his excellent study of process <u>improvements</u> in rayon manufacture at DuPont, lists and describes the source of 21 process improvements whose implementation required from one (e.g., "roller bath guides") to several (e.g., "cake to cone process") process machinery changes each - changes which he does not always enumerate. Hollander does, however, indicate whether the "source of technology" in each instance was DuPont, equipment manufacturers, or both. If we sort the improvements into these three source categories and sum, we find:

Novel equipment designed by:	
DuPont only	14
DuPont and equipment manufacturers	7
Equipment manufacturers only	0
Total	21

Hollander's data is obviously not really commensurable with ours - his purposes were different. Thus, he does not indicate whether the equipment developed by DuPont for internal use was later commercialized by equipment manufacturers; he does not trace the source of equipment brought to DuPont by equipment manufacturers (did <u>they</u> get it from users initially), etc. His work is very carefully done, however, and does clearly indicate a strong user role in the development of improved process machinery for rayon manufacture.

Interestingly, Hollander also lists three process improvements involving a change in the chemical composition of "baths" used in the process but no process hardware change. As we found was the case in our data, each of these was developed by a user.

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[18] The source of our data was Hollander[13], Chapter 7, "Sources of Technology Introduced at Spruance and Old Hickory", pp. 165-185. Each italicized heading listing a technical change which the body of the text indicated involved novel process equipment or equipment changes was coded as one "process improvement".

(2) Enos[14], in his excellent study of process innovation in petroleum refining, lists seven major process innovations as key advances in that art and indicates that three of them, The Burton Process, the Tube and Tank Process and the TCC Process, were developed by process users (oil companies). Three others, The Hondry Process, Hondriflow, and Fluid Catalytic Cracking were developed via joint ventures between users and non users while one, the Dubbs Process was developed entirely by a non user company. Each of these innovations was widely licensed throughout the petroleum refining industry and thus in this industry too, we find a strong user role in the development of key innovative processes and associated equipment.

(3) A study of innovation patterns in the machine tool industry[15] provides additional evidence for the generality of the user role in process and process machinery innovation. Portions of its discussion are focused directly on that issue, and we therefore quote as follows:

> Throughout its history the machine tool industry has responded to the demand of its users and has reflected the overall growth of industry. In England in the 18th and 19th centuries, new lathes were developed for the hydraulic press; new drilling machines were developed for the early steam engines. In the U.S., new production methods including what is now known as mass production, were developed by Whitney and Colt for the manufacture of guns. Firearms, sewing machines, bicycles, locomotives and automobiles all have had major impacts on the machine tool industry, and the machines and methods of production to which they gave rise are still in use. The aerospace industry is the most recent link in this chain of influence.
>
> User industries have affected innovation not only by creating new demands but by undertaking development on their own - as the automotive industry has developed new production lines and methods around standardized machine tool parts and as the aerospace and defense industries now develop their own metal forming methods.
>
> * * *
>
> The machine tool industry has been traditionally dominated by its customers. This has expressed itself in a number of ways. The industry has based itself on customer service, tailoring products to customer demands on what has been almost a custom basis, rather

than making products to a price and merchandising them. This has tended to make of the industry a gigantic job shop, with low production runs, high costs, low profits and high prices in comparison to the mass production machine tool industries of some other countries.

The industry has relied for direction in development work on what the customer wanted. In recent years, this has been particularly true of the machine tool industry's relation to the automotive industry. The automotive production engineers have tended to express their demands for machine tools three years ahead. Often they have specified the modified machines they want, and have handed specifications to the tool maker. In many cases, they represent the industry's development arm, so that the industry is particularly vulnerable to long-term change introduced from outside.

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